NONLINEAR MODELS FOR LATERAL DYNAMICS OF RAILWAY VEHICLES ON BRIDGES SUBJECT TO WIND ACTION

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19 June 2013

A CONFERENCE CELEBRATING THE 60th BIRTHDAY OF
EUGENIO OÑATE

Thematic Conference

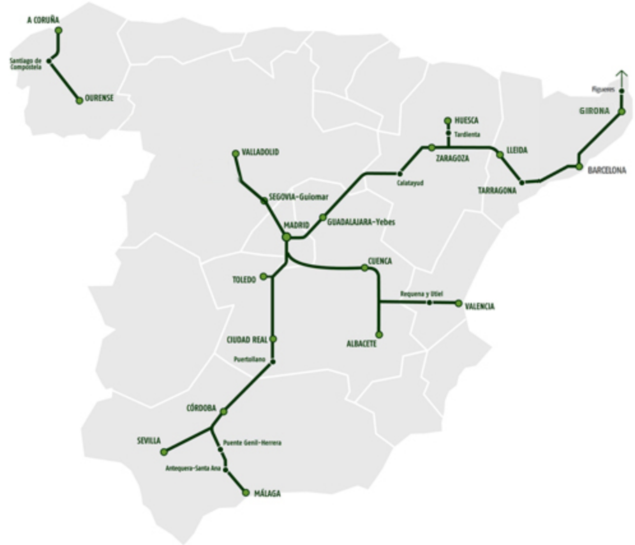
V International Conference on
Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2013

An IACM Special Interest Conference

17 - 19 June, 2013 Ibiza, Spain

Spanish High Speed Rail Network (2013)

3200 km of lines $v > 250$ km/h; 220 large viaducts

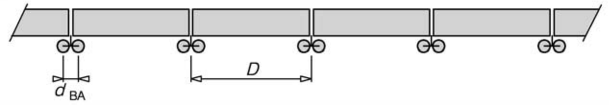


Contreras viaducts; Arch L=261 m. Madrid–Valencia.

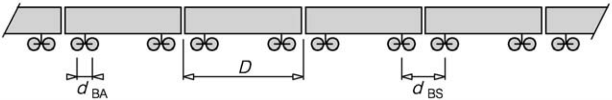
River Ulla. L=168 m, H=115 m. Orense–Santiago

Las Piedras. L=19×63.5=1206.5 m; H=92 m. Córdoba–Málaga

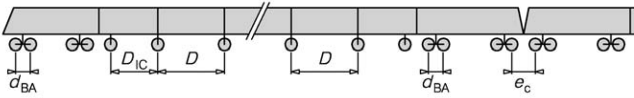
Trains on the HSR Spanish network



Articulated bogie trains



Conventional bogie trains



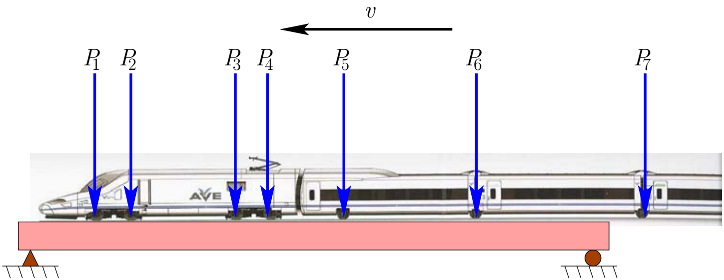
Regular single axle trains

Landwasser Viaduct. Albula Bernina Line (1903)

Outline

1. Vehicle-bridge interaction in railway dynamics
   - Railway infrastructure and trains
   - Vertical dynamics
   - Lateral dynamics
2. Models for vehicles and bridges
   - Vehicles: Multibody dynamics
   - Bridges: Finite Elements
3. Wheel-rail contact
4. Applications: strong winds on viaducts
   - Wind action
   - Critical Wind Curves

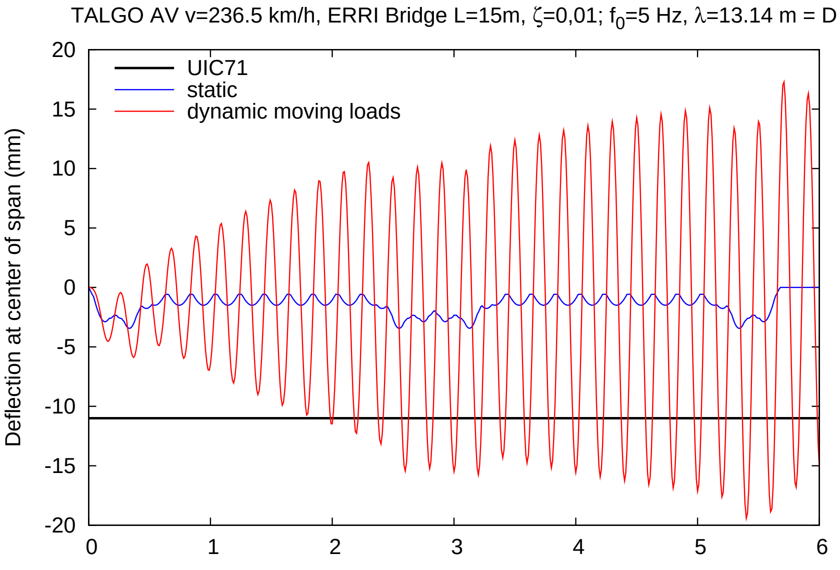
Dynamic effect of train



(Talgo HS train)

Dynamic effect of train: $v = 236.5$ km/h

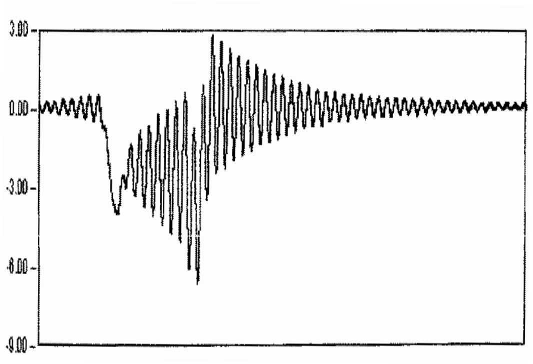
resonance!



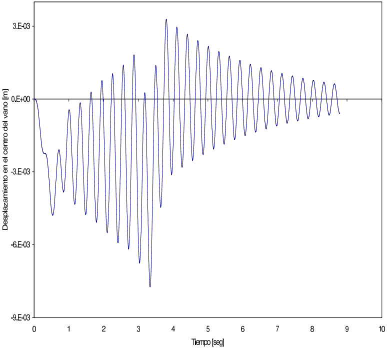
Tajo Viaduct (Madrid–Sevilla)

AVE S-100 $v = 219$ **km/h**

Vertical dynamic effects



Measured displacements [MFom 96]

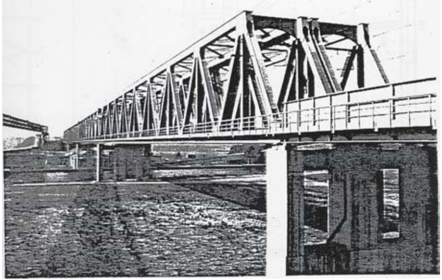


Computed displacements [Domínguez 99]

Lateral dynamics – ERRI D181 (1996)

- *European Railway Research Institute*, question D181
- Measurements and computations for lateral movement in several European bridges
- Mainly steel open decks

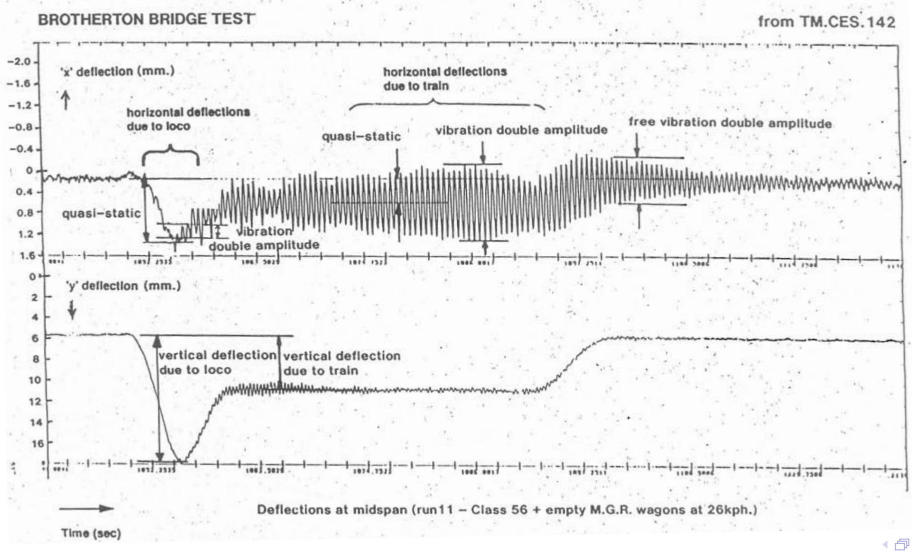
SNCB Bridge, Lixhe,
$L = 119.25$ m



Conclusions:

- EN1990: A2.4.4.2.4(3).— Frequency of lateral vibration of a span: $\boxed{f \geq 1.2\,\text{Hz}}$

Lateral and vertical displacement histories measured



Deflections at midspan (run11 – Class 56 + empty M.G.R. wagons at 26kph.)

Lateral dynamics – Relevance

- Contrary to vertical dynamic effects, usually they do not affect safety of structure

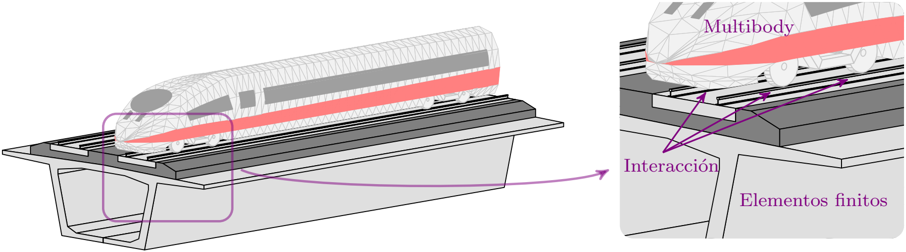
But they are critical for:

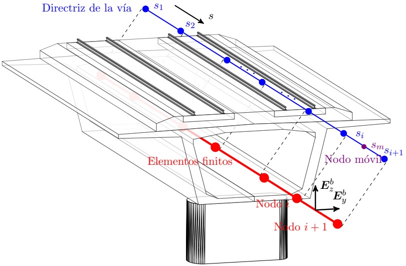
- Safety of vehicles and passengers
- Passenger comfort

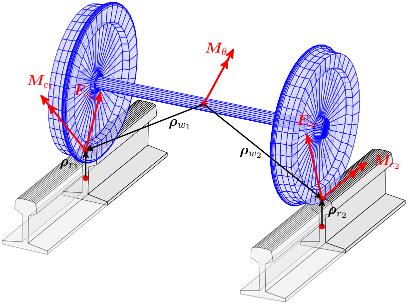
- Few studies: not well understood
- Coupled Vehicle-Bridge dynamic models
- Lateral nosing motion of wheels on rails
- Nonlinear effects for safety studies

Outline

Coupled, Nonlinear VBI models



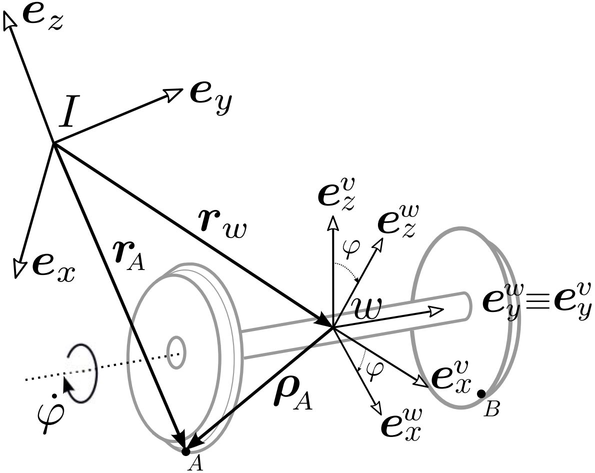




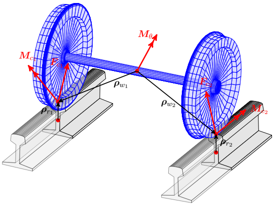
Multibody dynamics model:

- 7 rigid bodies $\times$ 6 dof
- Masses and inertias associated to each body
- Two suspension levels
  - Primary suspension (axles–bogie)
  - Secondary suspension (bogies–vehicle box)
  - User-programmed special rigid bodies (wheelsets)

Wheelset Rigid Element



- Wheelset reference frame
- Intermediate (no spin) reference frame



- Element in reference w/o spin

$$\underbrace{\boldsymbol{i}\dot{\boldsymbol{\omega}}_A + \boldsymbol{\omega}_A \times \boldsymbol{i}\boldsymbol{\omega}_A}_{\text{Inercia rotación Abaqus}} + \underbrace{\boldsymbol{i}\dot{\boldsymbol{\omega}}_\Psi + \boldsymbol{\omega}_A \times \boldsymbol{i}\boldsymbol{\omega}_\Psi + \boldsymbol{\omega}_\Psi \times \boldsymbol{i}\boldsymbol{\omega}_A}_{\texttt{Uel}} - \boldsymbol{m} = \boldsymbol{0}$$

- HHT-α time integration:

$$\boldsymbol{\omega}_{t+\Delta t} = \frac{\gamma}{\Delta t\,\beta}\,\Delta\boldsymbol{\theta}_t + \exp\left[\widehat{\Delta\boldsymbol{\theta}_t}\right]\left[\left(1-\frac{\gamma}{\beta}\right)\boldsymbol{\omega}_t + \Delta t\left(1-\frac{\gamma}{2\,\beta}\right)\dot{\boldsymbol{\omega}}_t\right],$$

$$\dot{\boldsymbol{\omega}}_{t+\Delta t} = \frac{1}{\Delta t\,\gamma}\,\boldsymbol{\omega}_{t+\Delta t} + \exp\left[\widehat{\Delta\boldsymbol{\theta}_t}\right]\left[-\frac{1}{\Delta t\,\gamma}\boldsymbol{\omega}_t + \left(1-\frac{1}{\gamma}\right)\dot{\boldsymbol{\omega}}_t\right],$$

- Newton linearisation:

$$\boldsymbol{i}\frac{\mathrm{d}\dot{\boldsymbol{\omega}}}{\mathrm{d}\boldsymbol{\theta}} - \widehat{\boldsymbol{i}\dot{\boldsymbol{\omega}}} + \boldsymbol{i}\hat{\dot{\boldsymbol{\omega}}} + (1+\alpha)\left[-\widehat{\boldsymbol{i}\boldsymbol{\omega}}\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}\boldsymbol{\theta}} + \hat{\boldsymbol{\omega}}\left(-\widehat{\boldsymbol{i}\boldsymbol{\omega}} + \boldsymbol{i}\hat{\boldsymbol{\omega}} + \boldsymbol{i}\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}\boldsymbol{\theta}}\right)\right]$$

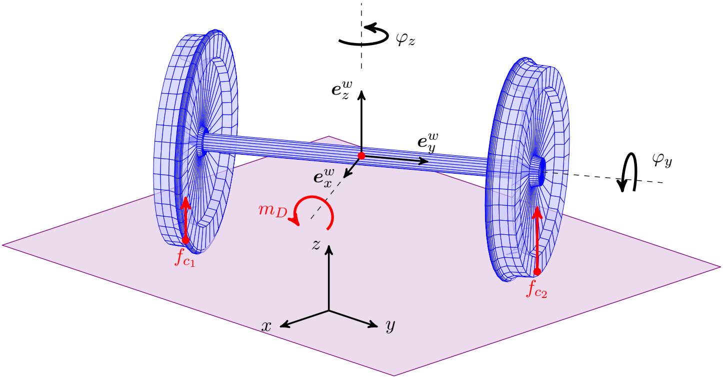
- Tangent operators:

$$\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}\boldsymbol{\theta}} = \frac{\gamma}{\Delta t\beta}\mathbf{T}(\Delta\boldsymbol{\theta}_t) - \widehat{\left[\boldsymbol{\omega}_{t+\Delta t} - \frac{\gamma}{\Delta t\beta}\Delta\boldsymbol{\theta}_t\right]},$$

$$\frac{\mathrm{d}\dot{\boldsymbol{\omega}}}{\mathrm{d}\boldsymbol{\theta}} = \frac{1}{\Delta t\gamma}\frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}\boldsymbol{\theta}} - \widehat{\left[\dot{\boldsymbol{\omega}}_{t+\Delta t} - \frac{1}{\Delta t\gamma}\boldsymbol{\omega}_{t+\Delta t}\right]},$$

$$\mathbf{T}(\Delta\boldsymbol{\theta}_t) = \boldsymbol{e}\otimes\boldsymbol{e} + \frac{||\Delta\boldsymbol{\theta}_t||/2}{\tan(||\Delta\boldsymbol{\theta}_t||/2)}\left(\mathbf{1} - \boldsymbol{e}\otimes\boldsymbol{e}\right) - \frac{1}{2}\widehat{\Delta\boldsymbol{\theta}_t}$$

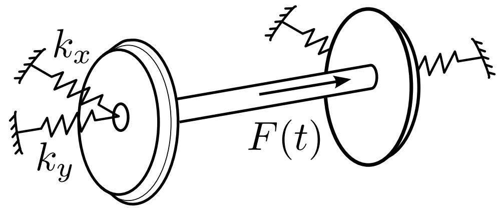
Multibody dynamics in 3D: Gyroscopic effects

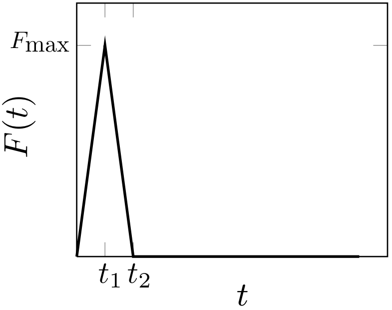


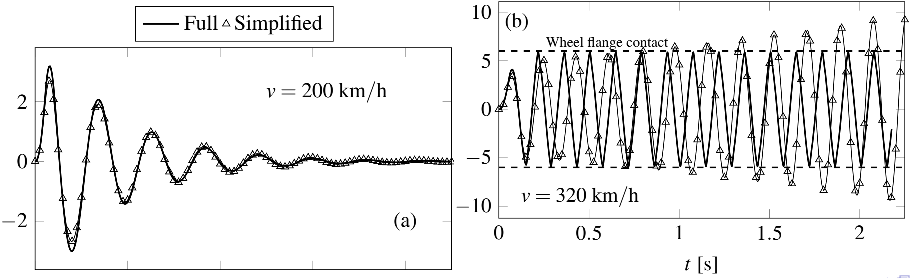
$$\boldsymbol{M} = \boldsymbol{I} \cdot \dot{\boldsymbol{\Omega}} + \boldsymbol{\Omega} \times (\boldsymbol{I} \cdot \boldsymbol{\Omega}) \quad \Rightarrow \quad \Delta f_c = \pm \frac{I_y \omega_y \omega_z}{2d}$$

In extreme scenarios, due to yaw under high speeds: $\boxed{\Delta f_c \approx \pm 5 - 10\% f_c}$

Hunting motion and flange contact



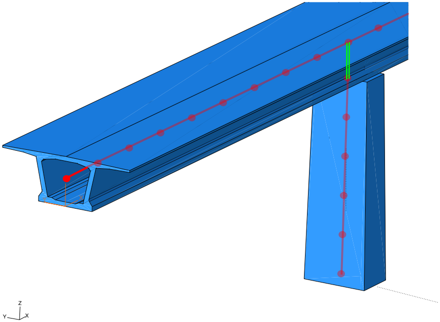


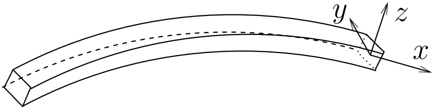


Models for the structure

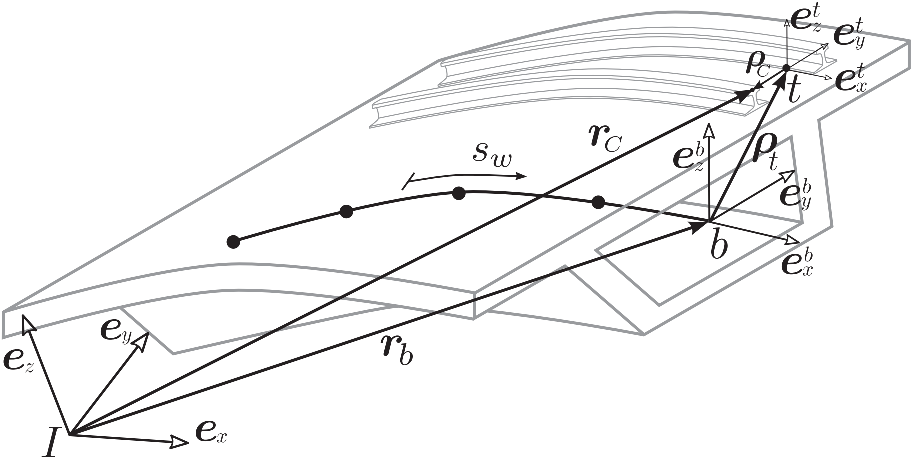
Finite elements (ABAQUS)

- Beam, shell or solid finite elements (3D)
- Linear elastic material
- Time domain, direct integration (HHT-α)
- User programmed constraints and interaction elements
- May be trivially generalized to more detailed models:
  - Shell and solid elements;
  - nonlinear material;
  - Large displacements or rotations





Geometry of Structure



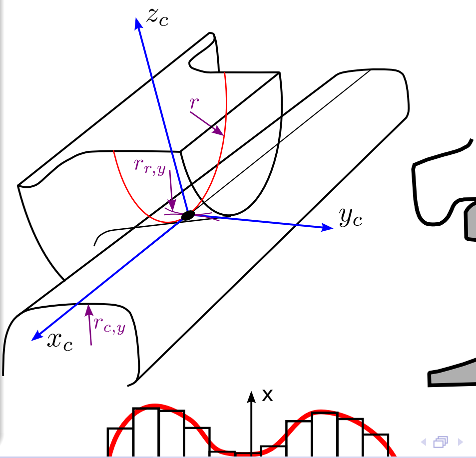
- Inertial reference frame (absolute coordinates)
- Bridge reference frame
- Track reference frame

Outline

Wheel–rail contact

Contact model

- Critical point in vehicle lateral dynamics
- Realistic profiles of wheels and rails considered
- Three stages of contact problem
  1. Geometric: contact point
  2. Normal force: Hertz model, contact ellipse
  3. Tangential force: Kalker's models (*linearised*, *FASTSIM*, *Pollack*, *Contact*, *Stripes*...)
- Semi-Hertzian models



Creep and tangential forces in wheel-rail contact

1) Rigid body slip:

a) Creepages:

$$\xi_x = (\boldsymbol{v}_w - \boldsymbol{v}_r) \cdot \boldsymbol{i}(1/v_0)$$
$$\xi_y = (\boldsymbol{v}_w - \boldsymbol{v}_r) \cdot \boldsymbol{j}(1/v_0)$$
$$\xi_r = (\boldsymbol{\omega}_w - \boldsymbol{\omega}_r) \cdot \boldsymbol{k}(1/v_0)$$

b) RB Slip at each point $\boldsymbol{x} = (x, y)^{\mathsf{T}}$ in the contact surface:

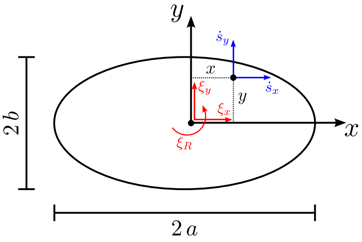
$$\{\boldsymbol{w}(\boldsymbol{x})\} = v_0 \begin{Bmatrix} \xi_x - \xi_r y \\ \xi_y + \xi_r x \end{Bmatrix}$$

2) Elastic tangential relative displacements $\boldsymbol{u}(\boldsymbol{x})$:

$$\dot{\boldsymbol{u}}(\boldsymbol{x}) = \frac{\partial \boldsymbol{u}}{\partial t} - v_0 \frac{\partial \boldsymbol{u}}{\partial x}$$

3) Total slip at each point:

$$\boldsymbol{s}(\boldsymbol{x}) = \boldsymbol{w}(\boldsymbol{x}) + \dot{\boldsymbol{u}}(\boldsymbol{x})$$

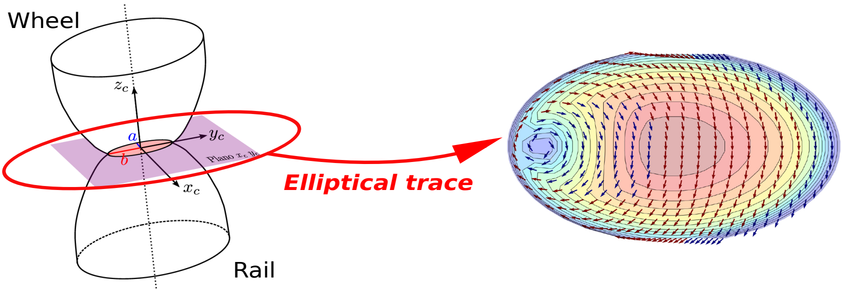


4) Tangential stresses: Coulomb law

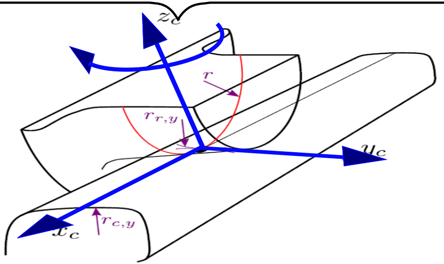
$$\begin{cases} \tau(\boldsymbol{x}) \le \mu p(\boldsymbol{x}) & \text{if} \quad \boldsymbol{s}(\boldsymbol{x}) = 0 \\ \tau(\boldsymbol{x}) = \mu p(\boldsymbol{x}) & \text{if} \quad \boldsymbol{s}(\boldsymbol{x}) \neq 0 \end{cases}$$

Hertzian+Fastsim contact model summary

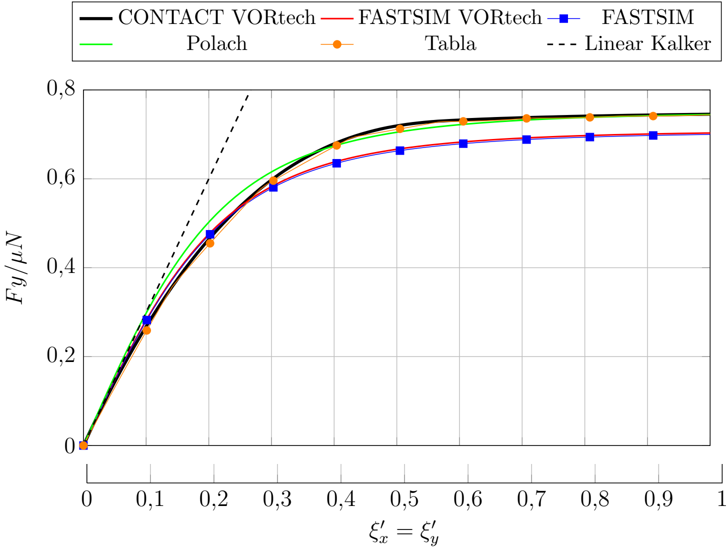
Normal contact: Hertz model **Tangential contact**



Resultant interaction forces

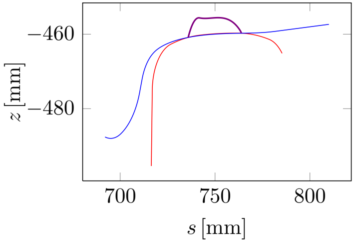


Tangential Contact Models

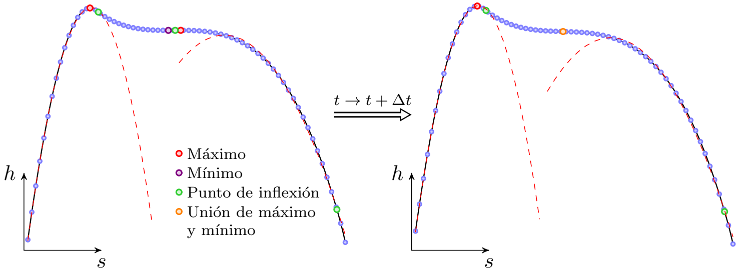


- Lateral load for $\xi'_r = 0$, $a/b = 1$

Determination of multi-hertzian contact geometry

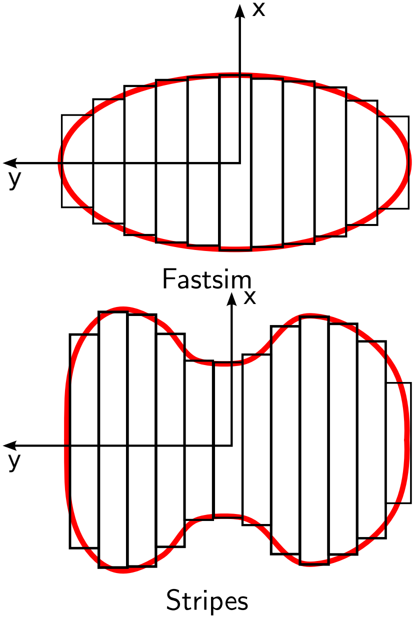


(a) Posición relativa de la rueda y del carril.



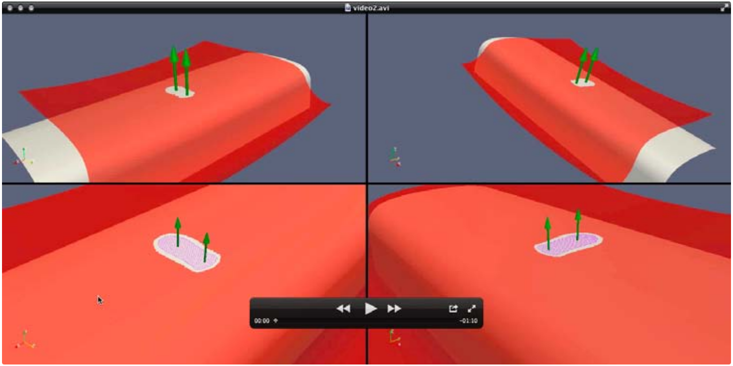
(b) Penetraciones $h(s)$ en dos instantes consecutivos.

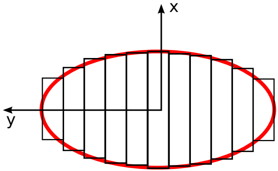
Fastsim and *Stripes*

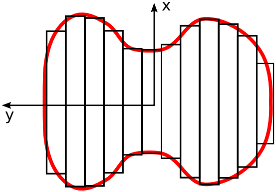


Stripes is a semi-Hertzian model, which applies Hertz's hypothesis only in x direction (longitudinal). In transverse direction contact may be multi-point

Stripes semi-Hertzian contact

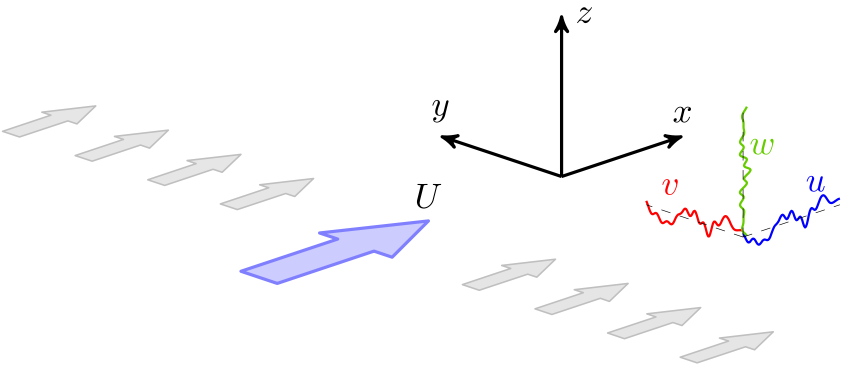






Outline

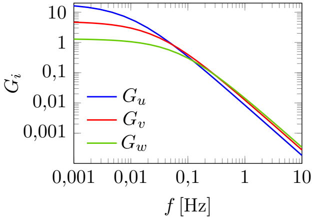
Modelling of wind action

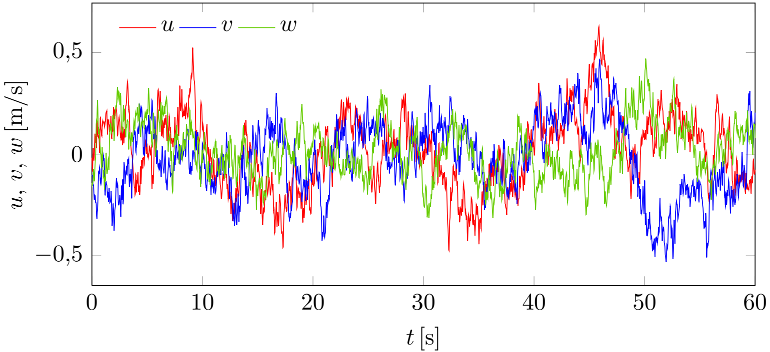


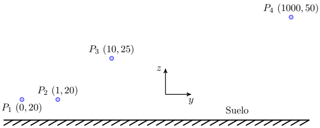
$$v(t) = \sum_{m=1}^{n_f} \sqrt{2\,G_v(f_m)\,\Delta f}\;\cos(2\,\pi\,f_m\,t + \phi_v^m)\,,$$

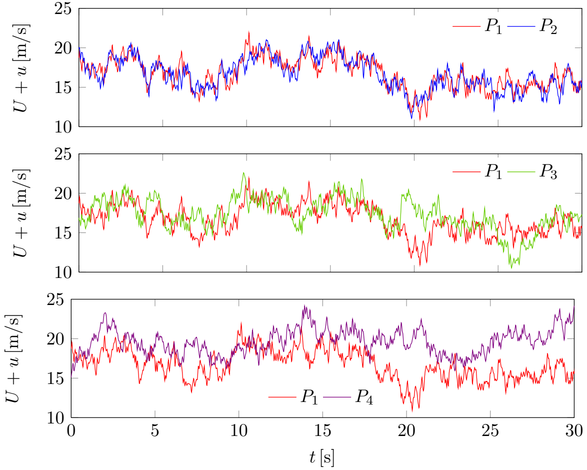
$$w(t) = \sum_{m=1}^{n_f} \sqrt{2\,G_w(f_m)\,\Delta f}\;\cos(2\,\pi\,f_m\,t + \phi_w^m)\,,$$

Modelling of wind action

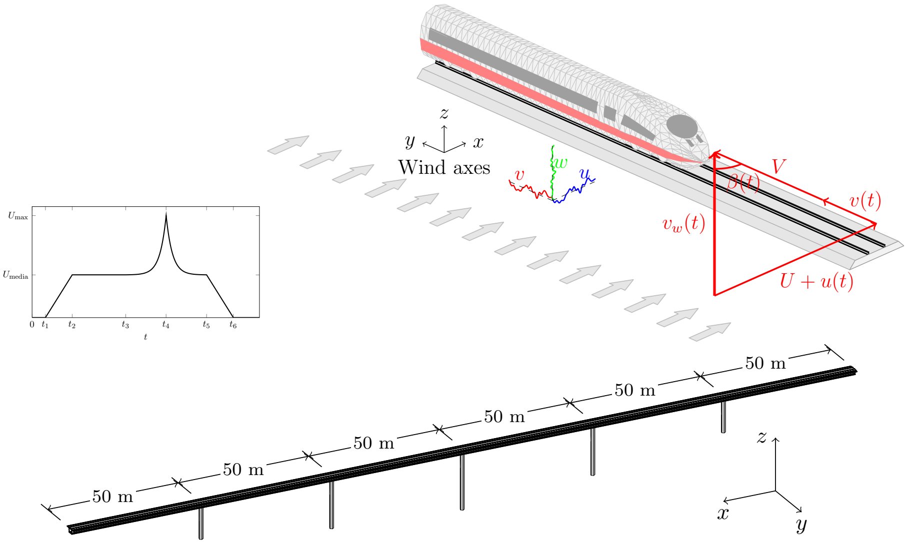




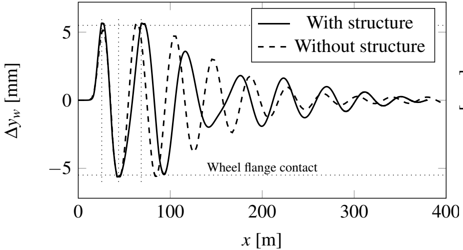

P_4 (1000, 50)
P_3 (10, 25)
P_2 (1, 20)
P_1 (0, 20)
z
y
Suelo

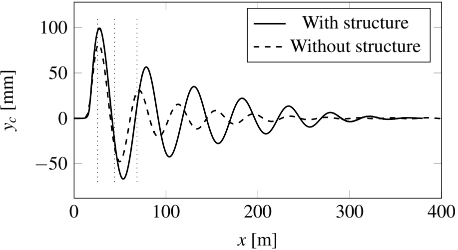

$U + u$ [m/s]
P_1
P_2
P_3
P_4
t [s]

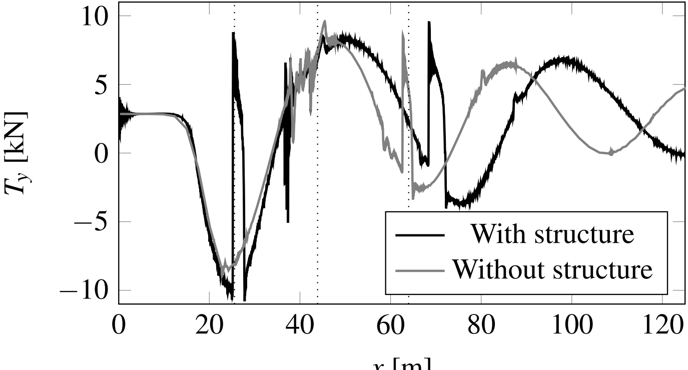
Wind gust on bridge: model



Wind gust on bridge: results



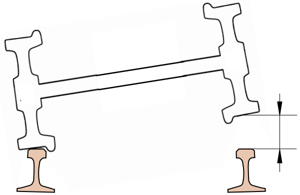




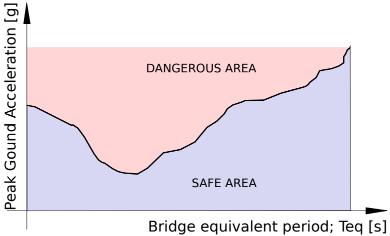
Criteria and critical curves

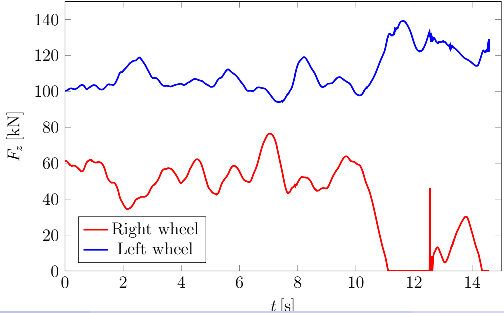
Matsumoto & Sogabe (2004), Japan RTRI

Derailment criterion:

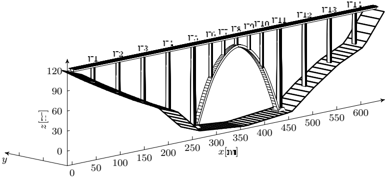


wheelset uplift > 25 mm

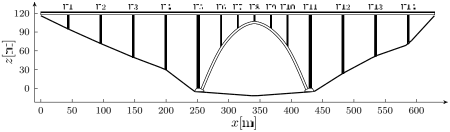




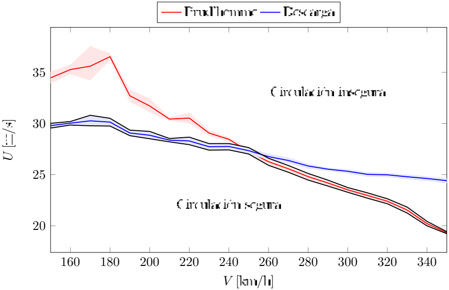
Critical Wind Curves on Ulla Viaduct



(a) Perspectiva.



(b) Alzado.



Elastic Wheelset